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Beach Morphology and Coastal Protection along Headland Bays in Cartagena de Indias, Colombia

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ABSTRACT

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This paper presents a morphological analysis of the beaches located on the central part of the Colombian Caribbean coast on the city of Cartagena de Indias. The beaches in this area are in bays constrained by headlands. The bays to the south of the area are heavily developed and influenced by the presence of coastal defense projects that include groins, detached breakwaters and seawalls. Conversely, the headland bays to the north of the area are predominantly free of human intervention. Analysis of the wave climate for the area is combined with morphometric analysis of beach and nearshore profiles collected at 34 locations during the period of August 2001 to January 2003, every two to four months. The morphology of the bays is used to identify the degree of exposure of the different beach segments to the prevailing conditions. Different segments were classified as exposed. Each of these zones has a characteristic beach profile morphology controlled by the local nearshore wave climate. Once the typical beach morphology was established for the natural beaches, it was compared to that of the developed beaches. Differences in morphology between the two types of bays are attributed to the coastal structures and their particular type.

ADITIONAL INDEX WORDS: *Beach profile, beach morphology, coastal structures, coastal management, Cartagena de Indias, Colombia.*

INTRODUCTION

Coastal erosion, partially due to rising sea levels, is often exacerbated by human interference that disrupts the natural sediment transport processes along the coastline. A typical example of a highly developed coastal region is along the Caribbean coast, where coastal tourism is one of the most important sources of income for the local population. It is not unusual for such development to take place without prior environmental impact studies.

In order to assess the effect of human interference on the coastal zone a baseline survey of the coastline must be established. Coastal morphology is the starting point for the development of such a baseline and it can serve as an initial step for assessing future environmental impacts. Further, it facilitates the process for a sustainable management of the coastal zone and the planning of further development.

The objective of this work is to present baseline information on the beach morphology along the coast of Cartagena de Indias, Colombia, a highly developed region. The coastline consists of a series of headland bays with a variety of coastal structures already in place.

The environmental setting of the area is first presented. Then the spatial variability of beach morphology along the beaches of these headland bays is examined. Finally, the role of different types of coastal structures in altering beach morphology is examined.

ENVIRONMENTAL SETTING

The study area is located on the central part of the Colombian Caribbean coast in the sector Galerazamba Bocagrande, between 75º 30.07´W, 10º 29.87´ N and 75º 32.86´ W, 10º 23.45´ N (Figure 1). The total length of the coast is approximately 26.1 km and it extends from Punta Canoas at the north through the coastline of the city of Cartagena, to Bocagrande at the southwest (Figure 1). The coastline is comprised of five headland bays with hard rock headlands accruing at both ends of each bay. Despite the difference in size (varying from 11,607 to 543 km) all bays have a similar shape with a high indentation at the northern (up drift) part of the bay.

Figure 1. Location map of the coastline in the vicinity of Cartagena de Indias, Colombia. Solid circles indicate the bench marks of beach and nearshore profile measurements.

The shoreline within each embayment is generally orientated along a NW-SE axis. The tide is mixed, mainly diurnal (form factor, F=1.54) with mean neap and spring tidal ranges of 0.20 and 0.55 m, respectively (average tidal range of 0.35 m - microtidal environment). Storm surges can raise sea level more than one meter above normal astronomical tide level (HASKONING, 1996).

Northeasterly winds are the most intensive and occur predominantly during the period of December to April with a mean speed of 7 m/s. The rest of the year southerly and southwesterly winds are prevailing. In addition to the seasonal variation, the winds vary at diurnal periods due to the development of a strong sea breeze that is responsible for modulating the nearshore wave climate (VERHAGEN and SAVOV, 1999). The offshore wave climate is typical of the Caribbean region and is characterized by wave heights between 1 and 7 m and mean periods between 4 and 12 s; the predominant wave directions are from the east and northeast (BRITISH MARITIME TECHNOLOGY, 1994; GIRALDO and LONIN, 1998).

METHODOLOGY

Beach profile data were collected during the period of August 2001 to January 2003, every two to four months at 34 stations at various locations along the bays (see Figure 1). Dry beach profile data were collected using land-surveying techniques (tachometer and level stations). These profiles extended from the top of the berm to a water depth typically around 1.8 m. In addition, nearshore profiles were collected from a boat equipped with a DGPS integrated with the HYPACK® navigational software and a chart-recording Raytheon (Model DE719C, 208 KHz) echo-sounder. The bathymetric surveys extended from the 2 m water depth to 1 or 2 km offshore (approximately 5 to 7 m water depth). The bathymetric records were manually digitized, and after being integrated with the positioning data, the water depths were corrected for tidal variation. The accuracy of the bathymetric surveys is estimated to be approximately 0.2 m in the vertical and 0.3 m in the horizontal.

Further, the different types of coastal structures and their extension were identified from aerial photos and *in-situ* surveys. In general, the following categories of coastal structures were identified: (i) groins, (ii) detached breakwaters, and (iii) concrete or riprap type seawalls. It should be noted that sediment accumulation behind the detached breakwaters has formed tombolo-like features so that the breakwaters can be considered similar to a T-shaped groin.

For each embayment, the headland spacing (R_o), the maximum indentation (a) and the obliquity of the dominant wave crests to the headland alignment (β) were calculated from the aerial photos and maps according to the methodology described in SILVESTER and HSU (1997, page 229) and KLEIN and MENEZES (2001). These parameters were used to estimate the exposure of the beach for each embayment using the indentation ratio (a/R_o). The effect of the headlands on the wave energy distribution was estimated using the non-dimensional embayment scaling parameter δ' (KLEIN and MENEZES, 2001; SHORT and MASSELINK, 1999):

$$\delta' = \frac{S^2}{m \cdot C \cdot H_b} \qquad (1)$$

where S is the embayment shoreline, m is the surf-zone slope, C is the width between the headlands and H_b is the breaking wave height.

Also, the dimensionless fall velocity parameter as adopted by WRIGHT and SHORT (1984) was estimated for each location:

$$\Omega = H_b / (W_s \cdot T) \qquad (2)$$

where W_s is the sediment settling velocity and T is the mean wave period.

The nearshore wave climate and breaking height (H_b) were estimated by means of wave refraction of the offshore wave climate using RCPWAVE (GRAVENS, 1992), while the beach slope was calculated from the measured beach profiles. In addition, depth of closure was estimated for each profile. This was defined as the location at which the variance of the profile exhibits a minimum. In this work, embayment orientation is defined as the orientation of the headland spacing line (R_o).

RESULTS

Nearshore Wave Climate

The beaches in Cartagena, because of their orientation, are influenced by offshore waves from the sector NE to SW (BRITISH MARITIME TECHNOLOGY, 1994). Representative offshore wave conditions were defined as those with significant wave heights of 1, 2 and 3 m (hereafter referred to as calm, moderate and high wave conditions, respectively) and with periods from 4 to 12 s. These wave heights have probability of exceedance of 27%, 14% and 6%, respectively, representing 57% of the total wave conditions. Storm wave conditions occurring 12 hours a year have significant wave height of 2.5 m and period of 8 s (HASKONING, 1996).

In order to assess the nearshore wave climate a total of 15 combinations of wave heights (1, 2 and 3 m) and periods (4, 6, 8, 10 and 12 s) were propagated toward the coastline using wave refraction and shoaling analysis (GRAVENS, 1992). The results indicated that in general, deep-water waves from NE and N change their directions to NNE-NNW when in the nearshore. Offshore waves with NW and W directions undergo little to no change in direction and height when arriving to the nearshore region of the coast, while waves from the SW change to a WSW-WNW direction.

Waves developed offshore in the Caribbean Sea affect the nearshore wave climate along the coastline of Cartagena de Indias for 37.2% of the year. The predominant nearshore wave direction is from NNE-NNW, occurring 35.19% of the year during the months of December to April. The second most important nearshore wave approach is from WNW-WSW, occurring during the period of May to November and corresponding to only 2.01% of the time. The remainder of the year (62.8% of the time) the nearshore wave conditions are influenced by local wind-generated waves.

The results of the refraction analysis for the Bocagrande area indicated that under moderate conditions the wave breaking height ranges between 0.3 and 1.2 m. During periods of storm and strong wind activity, breaking wave direction changes to predominantly NW-WNW with heights increasing to 1.5 and 2.4 m.

At the second embayment (Punta Santo Domingo to Punta Icacos), offshore waves from NE and N break with a height varying from 0.3 to 1.7 m generating surf zone widths between 80 and 140 m (extending to depths of up to 2.5 m). During storms and strong wind activity waves are predominant from WNW and NNW with breaking heights of 1.9 to 2.4 m.

Figure 2. Accretion to the north (right on the photo) of the Bocana groin (Boquilla beaches).

At the northernmost bay (Punta Manzanillo to Punta Canoas), low waves break at depths between 0.3 and 0.9 m while moderate wave breaker lines are located at water depths of 1.4 and 2.4 m. For high deep-water waves they are located between 1.9 and 4.3 m.

At all locations in the study area the predominant breaker wave types are plunging and collapsing.

Net sediment transport direction is predominately southwards, however during strong winds and storms with waves approaching from NW-W the local sediment transport can change direction towards the north.

Embayment Morphology

The beaches in the study area have a northeastsouthwest orientation. For the predominant wave conditions analyzed (NNE-NNW and WNW-WSW), the coastline is classified as wave-dominated and the embayments exposed to wave action.

The first embayment, located on the southern sector of the study area (Bocagrande beach), is a bow-shaped bay oriented 40º from North. It is constrained by two diffraction points. The northern end diffraction point is a small shoal (Santo Domingo headland) located off a seawall while the southern diffraction point is an artificially constructed long groin (Iribarren groin). The identation ratio (a/Ro=0.27) and obliquity (β= 24º) classify the site as an exposed, shallow embayment. For moderate and high wave activity the site is a dissipative (Ω>6) embayment with normal circulation (δ'>20), while for mild wave conditions (<1m) the beach can be classified as intermediate (3<Ω<5) with normal circulation (14<δ'<18). Beach material consists of fine sand (mean diameter from 0.14 to 0.21 mm, fall velocities 1.9 to 2.3 cm/s) and the average dry beach width is 50 m. The slope of the swash zone ranges from 0.7º to 3.2º and surf zone width between 20 and 270 m, depending on wave activity. The entire length of the coastline along this embayment is artificially stabilized. At the southern exposed sector, stone groins 97 to 300 m long can be found, while the northern, sheltered part of the embayment is dominated by a combination of stone seawall and groins. Historically, an erosional hot spot, activated during extreme storm activity, exists in the southern part, just upstream of the southern difraction point (i.e., Iribarren groin). An aeolian accumulation can also be identified at some places of this sector.

The next embayment to the north extends from Punta Santo Domingo to Punta Icacos, (see Figure 1) and includes the city beaches of Marbella, Crespo and La Boquilla. It is oriented 45º from North, and represents an exposed long downcoast tangent and a shorter sheltered zone with a shadow embayment (a/Ro=0.17; β=22º). A major part of the embayment beach is a long barrier spit that separates the coastal ocean from a swamp. The total width of the barrier spit varies between 35 m at the northern part and 1,500 m toward the southern exposed region. A seasonal, natural inlet occurs at the northern sheltered region that used to facilitate water exchange during periods of high rainfall. However, an artificial, stabilized and tidally controlled inlet (Bocana, see Figure 2) was recently constructed to facilitate tidal exchange resulting in the closing of the natural inlet. For breaking waves higher than 0.8 m, the bay is dissipative (Ω>6) and with normal circulation (δ'>20). For breaking waves smaller than 0.30 m, the beach behaves as that of intermediate type, with normal circulation.

The sediment on the southern straight and central parts of the embayment has sizes varying from 0.21 to 0.14 mm. The sand diameter decreases from south to north in this section and the swash zone has a low slope (2º to 1º). The width of the surf zone varies between 120 and 240 m. Evidence of aeolian accumulation exists at various locations along this segment of the embayment. The beach on the northern curved, sheltered part consists of sediment with particle size ranging from 0.15 to 0.18 mm, increasing northwards. The swash zone is almost flat (slopes < 1º) and the surf zone width varies between 150 and 700 m. No coastal structures exist at this segment of the embayment; structures (groins) can be found on the southern exposed part of the embayment. Erosion is experienced at the south end of the artificial inlet (6 to 20 m of shoreline retreat) and close to the stone seawall at the exposed strip of the embayment farther south. Accretion has been occurring at the north part of the Bocana groin with a mean shoreline advance of 52 m/yr (Figure 2), and at the north part of the now-closed seasonal natural inlet with a mean of 25 m/yr.

The next two bays to the north are the smallest found along the coast of Cartagena. They extend from Punta Icacos to Morro Medio and from Morro Medio to Punta Manzanillo. They are oriented 150º and 6º respectively from North and present relative shallow embayments (a/Ro=0.22; β=38º, and a/Ro=0.29; β=23º). They are classified as exposed and dissipative beaches with normal circulation. Beach sediment size varies from 0.17 to 0.21 mm with corresponding fall velocities ranging from 2.1 to 2.5 cm/s. For waves less than 1 m, beaches change to intermediate. Small to moderate levels of erosion from storm waves occur on the exposed southern part of these embayments.

The last bay of the series along the coast of Cartagena is

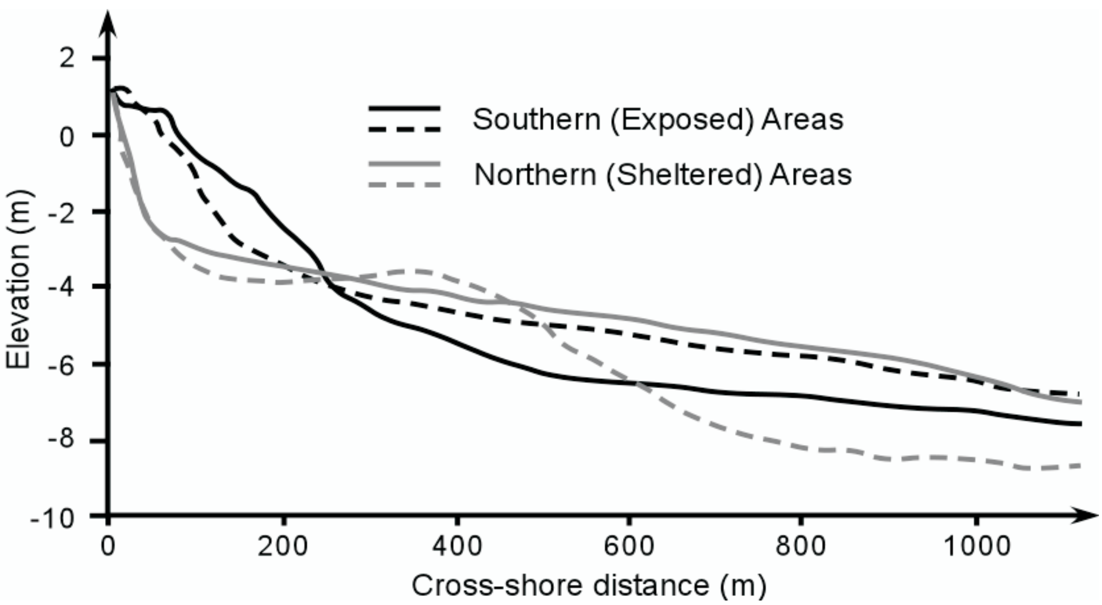

Figure 3. Typical nearshore profiles from the southern, exposed and northern, sheltered regions of the embayment in Bocagrande (mean profiles).

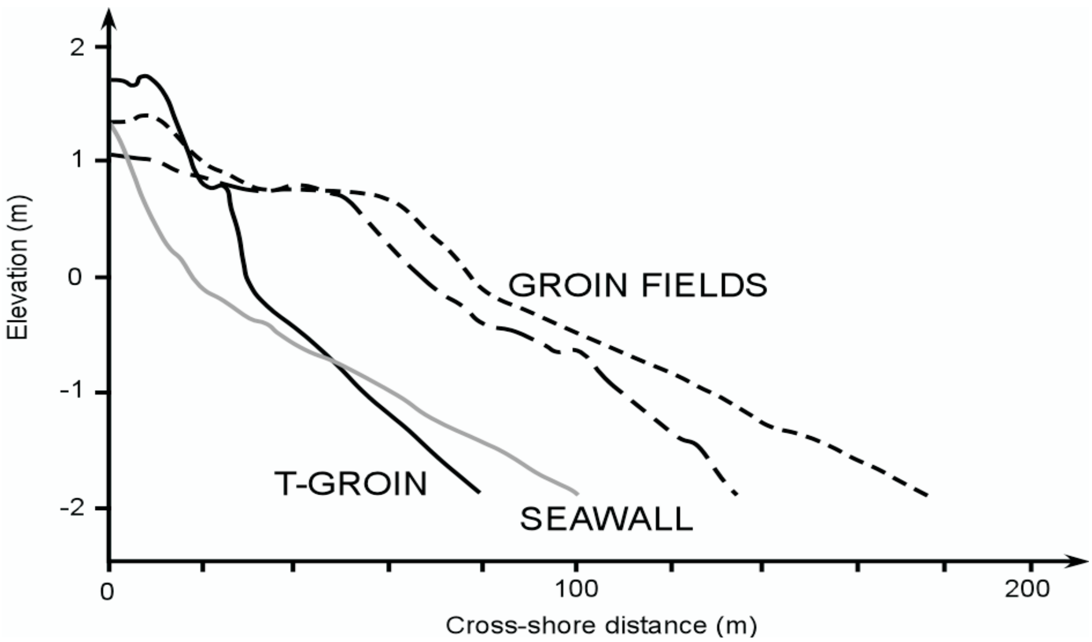

Figure 4. Typical beach profiles from the southern exposed regions at Bocagrande (within a groin field) and Punta Santo Domingo (in front of a sea wall and a T-groin, respectively).

oriented 167º from North and is constrained by two headlands: Punta Manzanillo in the south and Punta Canoas to the north. It is an exposed embayment (a/Ro=0.28, β=39º) and dissipative in character with normal circulation. Beach continuity is interrupted by a creek (Arroyo Guayepo) that discharges seasonally fresh water into the surf zone at the middle of the bay. Coastal structures are found on the southern, exposed part of the embayment, which has continually been eroded by storms. Some erosion is also observed to the south of the creek due to interruption of the longshore drift by the creek itself. To the north of the creek and on the sheltered north part of the embayment, accretion takes place resulting in an increased beach width.

Marine terraces consisting of sandstone and clastic deposits with thick clay matrix formations back the three northern embayments described above. These terraces are elevated up to 9 m above the mean sea level creating coastal scarps and cliffs. Beaches are narrow and flat (1º to 2º) with sand grain sizes ranging from 0.18 to 0.21 mm and surf zone widths between 150 and 400 m.

Spatial Variation of Beach Profiles

In general, beach profiles in the different embayments and sectors within each embayment are either linear or concave in shape with low slopes and some frontal dunes.

Beach profiles from the Bocagrande region are linear in shape with slopes of 0.6º to 3º. Dry beach width increases from south to north up to the central region of the bay. Thereafter, the width decreases from 40 to 10 m and increases back to 40 m at the northern sheltered part of the bay. Profiles with steeper slopes are located close to both headlands; the profile closer to the riprap seawall at the north presents a low protuberance and steeper slope (Figure 3). Closure depths for the southern and northern parts of the bay are estimated to be -5.3 and -5.5 m respectively, corresponding to distances of 390 and 560 m from the shoreline.

Beach profiles from the second headland bay (Punta Santo Domingo - Punta Icacos) exhibit different morphology for the regions north and south of Bocana (Figure 1). At the southern part (between Pta Sto Domingo and halfway to Bocana) the profiles are linear in shape with very small slopes decreasing from south to

Farther north, but still south of Bocana, the beach profiles are also linear in shape with slopes of 1º to 1.3º and moderate wide dry beaches (20 to 45 m) decreasing in width from south to north. In the nearshore, the profiles have slopes of >0.12º up to a depth of around - 4 m. Thereafter, they become flat without bars present.

To the north of Bocana the beach profiles are concave in shape and the dry beach width increases from 50 m to 115 m toward the north close to the location of the natural inlet. Farther north the dry beach width is becoming narrow again as the shoreline approaches the headland. The profiles in general, are flat with slopes decreasing from south to north. The nearshore profile has a slope of 1º to 0.6º at depths between 2.3 and 4 m and becomes much gentler sloping farther offshore. Most of the profiles in this region exhibit at least one or two bars while the closure depth for this sector is estimated to be at -5.6 m corresponding to a distance of approximately 2,000 m from the shoreline.

There is not enough profile information for the two bay sectors located up coast from Punta Icacos.

Data from the last embayment to the north (from Punta Manzanillo to Punta Canoas) show that beach profiles are linear in shape, especially in the region extending from south of the exposed zone to south of the Arroyo Guayepo creek (see Figure 1). To the north of the creek the profile is concave in shape. Closure depths are -4.5 m and located approximately 280 m from the shoreline. Dry beaches are narrow, increasing in width from south (10 m) to north (30 m). The nearshore part of the profile is flat, with decreasing slopes from south to north (0.75º to 0.5º). At the north headland, the profile changes its shape presenting a big protuberance, with a steeper nearshore slope (0.6º to 1º). Closure depth near the headland is -6.7 m located at a distance of 640 m from the coast.

Beach Profile Variability due to Coastal Structures

Beach profiles from sectors of the coastline with similar relative location within the embayments were compared for areas with and without coastal structures. In general, profiles present different forms and slopes depending on the type of structures close to them and their relative position within the bay. The differences are more pronounced for the sections of the profiles that are located in water depths less than 4 m (i.e., beach profiles).

At exposed (southern) sectors of the embayments, profiles located between groins exhibit wider dry beach widths than

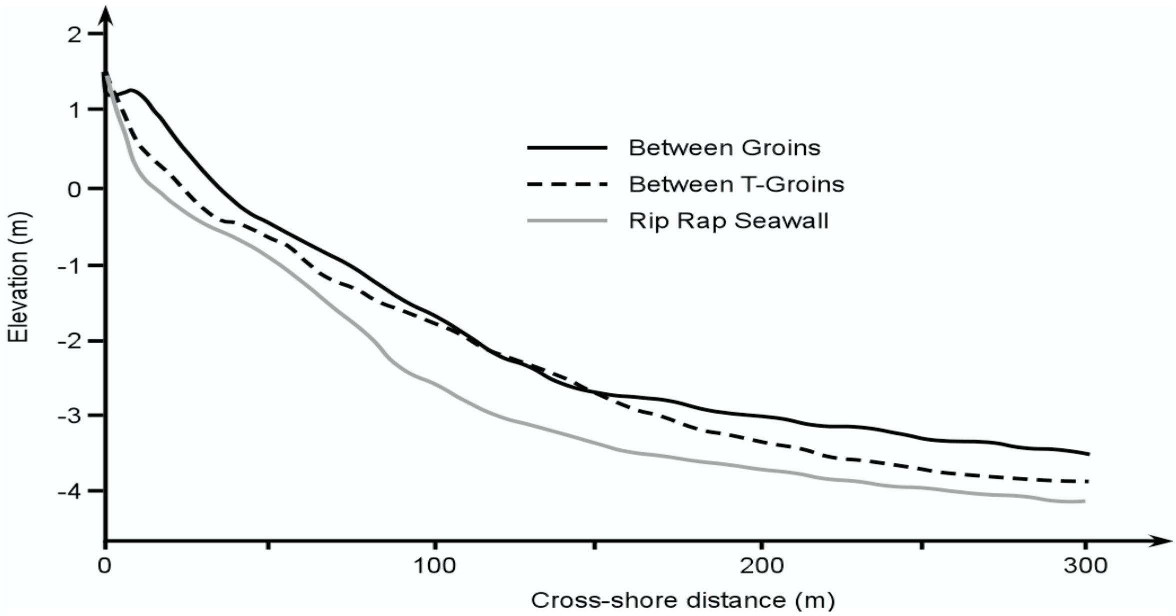

Figure 5. Beach profiles close to a groin, T-groin and rip rap seawall at the central region of the embayment at the Bocagrande and Santo Domingo-Boquilla areas.

those located between T-groins (i.e., offshore breakwater and tombolo) and in front of seawalls. The latter locations always produce a steep initial beach profile slope.

Beach profiles in areas with structures located in the central region of the bays (Iribarren-Punta Santo Domingo, and Punta Santo Domingo-Punta Icacos) do not show significant differences. However, profiles in groined areas tend to form wider dry beaches and some concave beach profiles. This appears to be more profound when the groins are very long. Riprap seawalls produce an initial steeper slope and narrow dry beaches with the latter being a function of the slope of the seawall (i.e., the bigger the slope of the seawall the wider the dry beach).

At sheltered sectors (based on observation from the Bocagrande beaches), dry beach width is the same for beaches between groins and in front of seawalls. However, the underwater part of the profile is steeper in front of the seawall than in the areas with groins (Figure 3, Bocagrande beaches).

Additionally, rip currents are present especially close to long groins in the Bocagrande and Bocana sectors, and inside T-groins at beaches to the north of the Santo Domingo headland (La Tenaza), where fatalities of swimmers have occurred.

Conceptual Model of a Typical Natural Bay at Cartagena Beaches

In general, beaches in the region of Cartagena de Indias in Colombia present some similar morphodynamic characteristics. Beaches have a northeast to southwest orientation (Figure 1); they are bow or parabolic shaped and classified as microtidal, exposed, with relatively shallow embayments (a/Ro less than 0.3); and predominant wave directions are from NNW to NW (predominant wave obliquity â<40º). Beaches are dissipative (Ω>6) for moderate and high breaking waves and intermediate (2<Ω<5) for low breaking heights (0.3 to 0.9 m high). For all wave heights considered, circulation of flows is normal (δ'>20). Sediments are fine to very fine sand with mean size diameters less than 0.21 mm. Dry beaches are wider (40 to 110 m) on the exposed southern sectors, decreasing in width toward the middle of the bay and increasing even more to the north, especially in response to perturbations such as that of the Bocana stabilization groin and the influence of the creek. Beach profiles are concave or linear near the coast while the nearshore parts are almost flat (<2º). Some of the profiles, especially on the northern, sheltered parts of the bays have bars present. Breaking wave types most frequently presented in the bays are plunging and spilling.

The analysis of the shape of the embayments indicates that they are not in static equilibrium. Figure 6 shows the relationship between the embayment indentation ratio (a/Ro) and the obliquity (β) of waves for the bays in this study. The dashed line indicates the relationship between the two parameters for the case of static equilibrium (SILVESTER and HSU, 1997). The embayments numbered as 2, 5 and 3 (see Figure 7) are farther away from a state of static equilibrium. This is further confirmed by the strong longshore sediment transport rates that exist in each location as revealed by the accumulation to the north of the Bocana groin and the Arroyo Guayepo creek. Figure 7 presents the deviation of the embayment shape from the static equilibrium shape (dashed

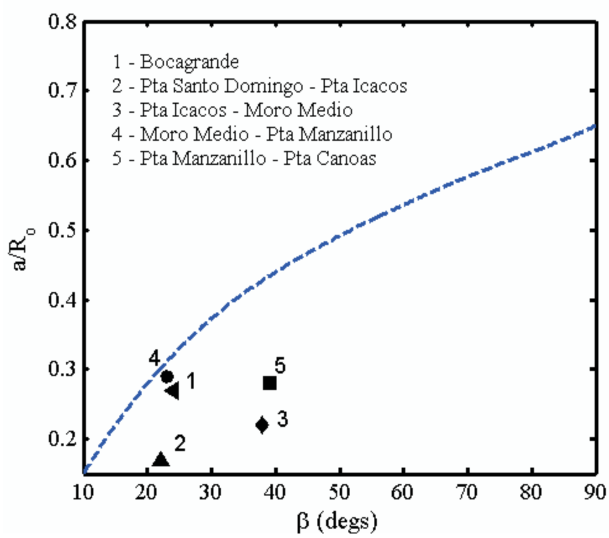

Figure 6. Diagram showing the relationship between the embayment indentation ratio (a/Ro) and the obliquity (b) as measured from the air photos and maps. The dashed line indicates static equilibrium conditions (SILVESTER and HSU, 1997). All embayments have an obliquity smaller than 40^{o} indicating exposed beaches. Also, regions 2, 5 and 3 appear to be further away from a state of static equilibrium.

lines) for the three larger embayments. The net sediment transport directions for some locations as inferred from field observations are also shown. Field observations of longshore currents have shown that longshore sediment transport direction can change throughout the year. During storms, waves from NW-W change longshore currents and associated sediment transport directions. During these events material moves northward and accumulates in the sheltered areas. Once there, it is difficult for this sediment supply to move back southward when the wave conditions change. This is the mechanism by which sediment accumulation occurs at sheltered zones as shown in Figures 7 and 2 (north of Bocana long groin) and a delicate dynamic equilibrium condition exists that defines the shape of the embayments which appears to be different of that of static equilibrium.

SUMMARY

Beaches with a headland geomorphology on the Cartagena de Indias coast in this study were classified using morphometric and morphodynamics parameters such as distance between headlands, wave obliquity, indentation ratio, sand size, near shore slope, and wave breaker height and periods. Coastal bays have a northeast to southwest orientation and are bow or parabolic shaped. They are classified as microtidal, with relatively shallow embayments (A/Ro less than 0.3) and a predominant small wave obliquity (β 40º) indicating exposed beaches.

The beaches are dissipative ($\Omega > 6$) for moderate and high breaking waves, and intermediate ($2 < \Omega < 5$) for low breaking heights (0.3 to 0.9 m high). For all deep-water wave heights considered (1 to 3 m), circulation of flows is normal ($\delta' > 20$). Sediments are fine to very fine sand with mean size diameter less than 0.21 mm, varying from south to north within the bays. Dry beaches are relatively wide. Beach profiles are linear or concave in shape, some of them with dunes, and have flat slopes ($\leq$ 2º; 1:100 to 1:200) decreasing to the north headland and ending with flatter nearshore profiles (<2º), some with one or two bars. Breaking depths for the majority of waves occur between 0.2 and 2 m with predominant breaker types plunging and spilling.

Beaches are not in a state of static equilibrium as predicted according the SILVERSTER and HSU, 1996. During storms, waves change the sediment direction to the north, where diffracted waves may not remove it during predominant wave conditions.

Coastal structures modify beach width and beach profile forms depending on their location inside the bay. Beaches at the southern, more exposed sections close to or between groins present wider dry beaches (50 to 80 m) with less concave and more linear beach profiles than natural beaches, and flatter slopes (0.8º to 1º).

At the less exposed sectors, the presence of groins produces mild beach slopes and relatively narrower beaches than those at exposed sectors. Groins set close to sheltered sectors tended to decrease the profile slopes without increasing beach width especially if seawalls are present. Rip currents are also present, especially close to long groins in Bocagrande and Bocana, and inside T-groins at beaches in the Santo Domingo area.

The spatial variation of beach morphology by coastal structures as described earlier, is a first approximation of the effects that coastal protection structures cause. It appears that parameters such as groin length or slope of seawall are important in defining the dry beach width, the most economically important part of the beach, but also the existence of potentially dangerous return flows.

This work described qualitatively the coastal setting for the region of Cartagena de Indias, Colombia. The data collected created a database for evaluating future evolution of the coastal region and for assessing the effects of future human and natural phenomena on the coastal zone.

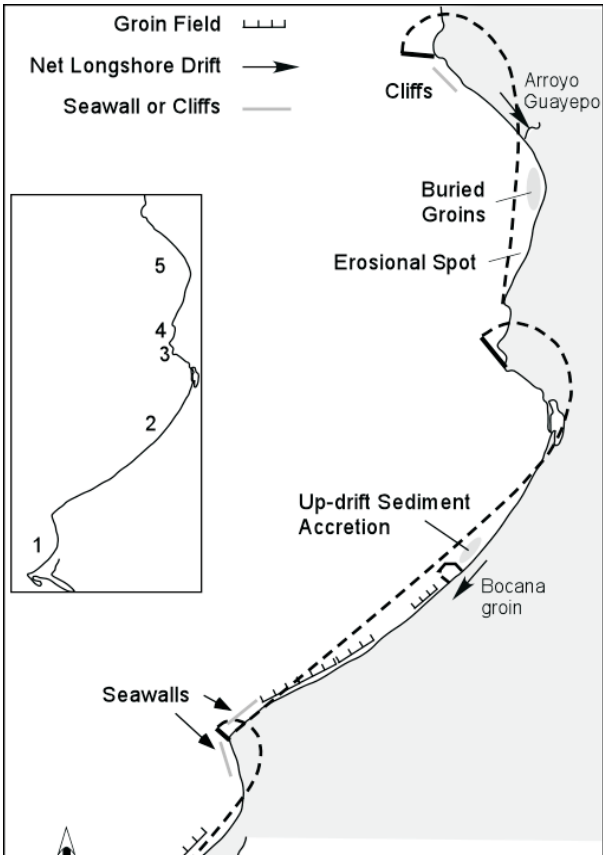

Figure 7. Synthesis figure for the beaches of Cartagena de Indias. The deviation of the embayment shape from the static equilibrium shape (dashed lines) as predicted according the SILVERSTER and HSU (1996) is shown for the three larger embayments.

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